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INTERFERENCE MANAGEMENT IN HETEROGENEOUS NETWORKS

UNIVERSITY OF MARYLAND

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FINAL TECHNICAL REPORT

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14. ABSTRACT

Deployment of low power “pico” base stations within the existing cellular networks can potentially increase both capacity and coverage. However, such deployments require efficient frequency allocation schemes for managing interference from the pico- and macro base stations that are located within each others’ transmission range. Partitioning the available frequencies between the various base stations avoids the problem of interference, but can lead to inefficient spectrum usage.

This effort developed a distributed interference management frequency allocation scheme that *shares* frequencies between macro- and pico-base stations, and guarantees a minimum average throughput to cell users. The scheme minimizes the number of frequencies used. In the detailed simulations, the developed scheme outperforms a static frequency reuse scheme and the centralized optimal partitioning between the macro and picos. Moreover, the scheme performs on par with the centralized optimum allocation.

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1 Summary

Deployment of low power “pico” basestations within the existing cellular networks can potentially increase both capacity and coverage. However, such deployments require efficient frequency allocation schemes for managing interference from the pico- and macro basestations that are located within each others’ transmission range. Partitioning the available frequencies between the various basestations avoids the problem of interference, but can lead to inefficient spectrum usage.

This effort developed a distributed interference management frequency allocation scheme that *shares* frequencies between macro- and pico-basestations, and guarantees a minimum average throughput to cell users. The scheme seeks to minimize the number of frequencies used. In the detailed simulations, the developed scheme outperforms a static frequency reuse scheme and the centralized optimal partitioning between the macro and picos. Moreover, the scheme performs on par with the centralized optimum allocation (solved by a centralized linear program).

2 Introduction

Augmenting the macro BSs with low-power BSs provides a scalable solution for increasing the capacity of the network [7, 1, 11]. Service providers can deploy these “pico” BSs in high-density areas (e.g., malls, stadiums). BSs can take advantage of low pair-wise interference (macro-pico or pico-pico) to share spectrum, thereby improving the aggregate throughput in the network.

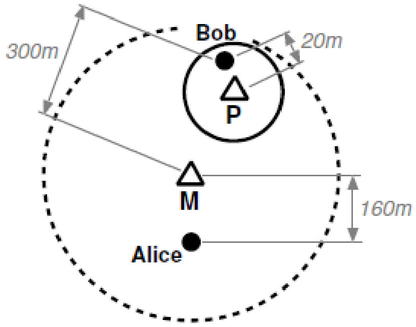


Figure 1 : Example topology consisting of two BSs (M,P) and two users (Alice,Bob). Note that this figure is not to scale.

For example in Figure 1, BS M transmits at 50 dbm, and BS P transmits at 10 dbm and is contained in M’s coverage area. Alice is associated with M, while Bob is associated with P. Given that M’s coverage area extends across the entire region, Bob receives some interference when both M and P transmit on the same frequency. In contrast, due to P’s low transmit power, Alice receives little interference from P.

Partitioning the available spectrum assigns different frequency resources to each BS (and thus each user). However, since Alice sees little interference from P, M can share any frequency it allocates for Alice with P (and in turn with Bob). Suppose that P can serve Bob at a data rate of 540 kbps using a frequency shared with M. Then, compared to the throughput of, say, 810 kbps for one exclusive frequency for Alice, a shared frequency can achieve an aggregate throughput of 1350 kbps. This example shows how sharing can reduce spectrum required by the network.

Frequency spectrum is a limited and increasingly expensive resource. In a cellular system there is a constraint on the total number of frequency resources and an inefficient allocation of the frequencies might lead to unsatisfied users. In this work, we explore the generalization of the above example involving multiple pico BSs (PBSs) within the coverage area of a macro BS (MBS). Our goal is to meet the minimum throughput requirements for all users, while *minimizing* the total spectrum usage. Prior work in this area uses coarse-grained feedback from users to assign frequency resources. We improve on this model by incorporating more fine-grained feedback from users, calculating the expected throughput rates at each user when nearby BSs broadcast interfering transmissions.

A frequency resource used by a particular BS may be further re-used by a set of other BSs in the system. The re-use is called sharing of the frequency resource. The rate supported on the shared spectrum for a user is a function of the user position in the serving BS, and also the placement of the neighboring BSs. The position of different users associated with the interfering BSs provide us with an extra degree of freedom, to share aggressively even amongst the interfering BSs and hence utilize the available spectrum more efficiently. We try to explore this extra degree of freedom in this work for 1-Tier unplanned cellular networks as well as 2-Tier heterogeneous cellular networks.

We first model this allocation problem as a centralized linear programming problem, followed by the introduction of a distributed heuristic algorithm. We first focus on the homogeneous (1-tier) network consisting of pico BSs, and then modify the initial approach to fit the heterogeneous (2-tier) network by also considering the macro BS. We finally describe our simulation environment, and evaluate our algorithm against the LP solution and other solutions in prior work.

3 Related Work

Interference avoidance, interference management and interference cancellation techniques have been proposed to counter the interference in the unplanned cellular network of low-power BSs deployed in coverage regions of existing MBSs. A broad survey of these techniques is given by Perez et al. [17]. A centralized optimal power control and resource allocation problem for 2-tier network is formulated in [13]. As discussed in [17], the computational complexity of solving the minimization problem can be prohibitive if the number of low-power BSs is large. This problem is exacerbated by user arrivals and departures as well as inter-cell mobility, since each such event triggers a recomputation. In the rest of this section, we discuss prior work that provides heuristic solutions.

Perhaps the simplest resource allocation technique in multi-BS scenarios is to partition frequencies between BSs. Prior work has explored probabilistic methods for partitioning the frequency space without assuming coordination between different transmitters. A randomized hashing algorithm is proposed in [19] to avoid collision of frequency resources with interfering femto BSs. In [6], the authors use F-ALOHA spectrum access to avoid persistent collision with interfering femto cells in their allocated spectrum. Our work, in contrast, assumes coordination and communication between PBSs and MBS and allocate spectrum more efficiently.

In general, an MBS can be allocated frequencies exclusive from other low-power BSs [6, 16, 4, 19] to completely eliminate the cross tier interference. However, as noted in [17] and by our results, partitioning frequencies is inefficient.

The coupled model in [19] does introduce a sharing model based on femto BS locations with respect to MBS. However, the sharing does not take user location (within the femto cell) into account, which can lead to low SINR for a poorly positioned (cell-edge) user. In our work, we share frequencies by explicitly taking the user locations (and achievable SINR) into account.

The idea of sharing spectrum amongst the interfering BSs to increase spectral efficiency is not new. The cell geometry assumed in the literature for homogeneous cell scenario is symmetric hexagons, with each BS equidistant from its neighboring BSs. Fractional frequency re-use schemes have been proposed in the literature [12] to maximize the spectral efficiency of the cellular system. In these schemes, a cell is divided into two regions, an inner region comprising users close to the BS and an outer region which contains users that are farther away from the BSs. Neighboring BSs can share frequencies used within inner regions. However, to minimize interference, the outer regions of neighboring BSs use different frequencies. Such a frequency sharing framework can be inefficient if we assume an unplanned cellular network or one where BSs are added based on demand (hotspots) since the demarcation between inner and outer regions no longer remains uniform.

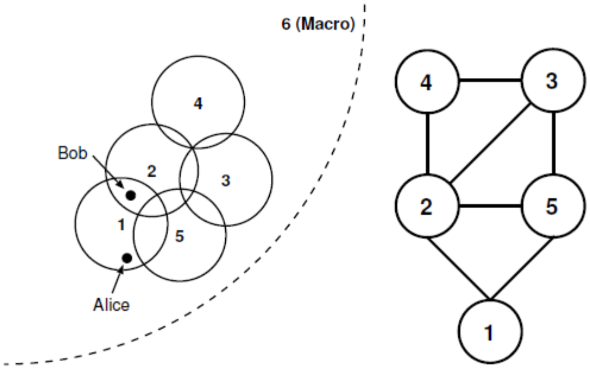
Some of prior work has also considered scenarios where a mobile user is allowed to share its frequency resources with the interfering BSs only if the user is guaranteed a minimum SINR [14, 15]. Sharing frequency resources amongst interfering femto-cells is also the focus of [18]. The interference model in [18] captures the interference amongst all the users in the system rather than low-power BSs; each user is assumed to require one resource block irrespective of their position in the associated cell (hence this model ignores individual user requirements). Under this model, the frequency allocation problem can be modeled as a (centralized) vertex coloring problem with every user in the system modeled as a vertex requiring a single color. We compare our techniques to vertex coloring algorithms in Section 8.

Other work, e.g., [5], explores the same idea by using a heuristic coloring technique for non-interfering femto BSs in the first stage. The algorithm in [5] includes a second stage in which each femto-cell user sends a request to the adjacent BSs to share their resources. The request is granted by the BSs under the constraint that every user is guaranteed a minimum SINR. We note that in both [15] and [5], the use of shared frequencies is based on a fixed SINR threshold, which leads to a somewhat more restrictive sharing model.

Finally, we note that interference cancellation techniques have been proposed [10, 8] but remain impractical due to the difficulty of eliminating errors in the cancellation process and the cost of custom hardware [17].

4 System Model

We consider a network consisting of one MBS and multiple PBSs within its coverage area. Figure 2a shows an example network topology. Our algorithm can be extended to the frequency allocation algorithms to fit scenarios with more than one MBS. We first study a homogeneous (1-tier) network of (pico) BSs, where all BSs use the same transmit power. We then present a topology including the MBS, forming a heterogeneous (2-tier) network.



(a) Topology (b) Conflict Graph

Figure 2: Example topology containing 5 PBSs inside the coverage area of a MBS BS-6. The conflict graph for the Distance based interference model is shown without the macro node (6), which has edges to all other nodes.

We focus on the frequency resource allocation problem for downlink communication between the BS and the users. We assume a fixed association scheme (except when we consider user arrivals and departures) where users choose the BS that provides them the highest SNR, with a 6 dB bias towards choosing a PBS. Although it may be possible for multiple BSs to serve a user, we chose to consider only the single association case. In addition, we do not consider spatial diversity that can be provided by multiple transmit antennas, which may permit simultaneous scheduling of more than one user on the same frequency at a single BS.

We model the network as a conflict graph $G=(V,E)$, where each vertex $v \in V$ represents a BS in the network. Undirected edges $e \in E$ capture the presence of non-negligible interference at users within a pair of BSs. We say that two BSs BS-i and BS-j are *neighbors* when there is an edge $e=(i,j) \in E$.

We use a *distance-based interference model* (DIM) to define the edges in the conflict graph, in which two PBSs are neighbors if their distance is less than a certain threshold value. In Figure 2a, the solid circles surrounding each PBS ($PBS_1 - PBS_5$) represent half of this distance. Therefore, two PBSs are considered neighbors if their circles overlap. In our model, the MBS is assumed to be a neighbor to all PBSs.

The data rate for a user is largely determined by the signal strength at the user from the serving BS, as well as the interference present from any non-serving BSs sharing the same frequency. We capture the interference experienced by a user by considering the transmit power at the neighboring BSs of the user's serving BS.

A BS can share a frequency resource with its neigboring BSs based on the interference caused by them. A BS might even choose to not share its frequency resource with any of its neighboring BSs and hence have an exclusive frequency resource. It is assumed that any two users associated with the same BS cannot use the same frequency resource at a given time.

4.1 Mapping to LTE Networks

A single frequency resource in the LTE standard of OFDMA cellular system consists of a set of subcarriers, called a frequency resource block (FRB). One FRB spans a frequency band of 180 kHz in the LTE standard, which consists of 12 subcarriers separated by 15 kHz between two adjacent subcarriers.

In a 2-tier network, we assume that all PBSs are connected to the MBS through a wired backhaul connection. This backhaul connection can be provided using a fiber cable. However, microwave backhaul connections are emerging as a more practical solution due to the time and cost of setting up a fiber connection [2, 3]. The capacity of a microwave backhaul connection between a MBS and PBSs is constrained to hundreds of Mbps [3].

As a cluster of PBSs may have a large number of users during peak hours (e.g., during a football game), signaling traffic on the backhaul needs to be limited. This restricts coordination between BSs, which makes the frequency allocation problem more challenging.

5 Centralized Allocation

Our frequency resource allocation scheme aims to minimize the total number of FRBs needed to provide the minimum throughput required by the users. Sharing of FRBs can be used to minimize the number of FRBs, when some of the users can tolerate the interference present from neigboring BSs. We assume each BS has a knowledge of the average throughput its users can expect when a FRB is shared with any subset of the neighboring BSs.

We provide a list of notations and their meanings in Table.1.

Table 1: Notations and associated definitions

Notation	Description
b, o	A BS in the network
$\mathcal{B}$	Set of all BSs in the network
C	A nonempty set of BSs in the network
$B(u)$	BS to which user u is associated
N_b	Set of all neighbors of BS b
x_C	Number of FRBs shared among the BSs in C
$y_{C,u}$	Number of FRBs assigned to user u, which are shared among the BSs in C
T	A FRB type
$O(t)$	BS which owns FRB type t
$P(t)$	Set of participating BSs in FRB type t
$\mathcal{T}_b$	Set of all FRB types owned by a BS b
$N(t)$	Number of FRBs of type t
$c(t)$	Cost associated with FRB type t
L_u	Sorted list of FRB type for user u according to decreasing efficiency
$\mathcal{C}(t,b)$	Compatible set for FRB type t with respect to BS b
$\mathcal{E}(t)$	Extended compatible set of type t
$\mathcal{U}$	Set of all users in the network
$\mathcal{U}_b$	Set of users associated with BSb
$r_{u,C}$	Expected throughput for the user u when it is served by a FRB type shared with the BSs in C
req_u	Average throughput requirement of the user u

Suppose that $C\in\mathcal{P}(\mathcal{B})\setminus\emptyset=\mathcal{C}^\star$, i.e., a non-empty set of BSs, where $\mathcal{P}(\mathcal{B})$ denotes the power set of $\mathcal{B}$. For each BS $b\in C$ and user $u\in\mathcal{U}_b$, let $r_{u,C}$ denote the expected throughput of user u when it is served by a FRB shared with the BSs in C. Each user estimates these rates by measuring the strength of the pilot signals transmitted by each of the neighboring BSs, and then reports the *rate vector* to its associated BS.

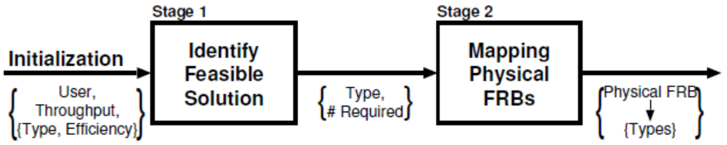
We formulate the problem of minimizing the total number of FRBs as a linear programming (LP) problem. For every $C\in C^\star$, let x_C denote the number of FRBs shared among the BSs in C and $y_{C,u}$ refine x_C for a specific user u. We define $\mathbf{x}=(x_C, C\in C^\star)$ and $\mathbf{y}=(y_{C,u}, C\in C^\star \wedge u\in U)$. The following minimization problem provides us with a lower bound to the solution:

$$\begin{aligned} &\min_{\mathbf{x},\mathbf{y}} \sum_{C\in\mathcal{C}^\star} x_C \\ &\text{subject to} \sum_{C\in\mathcal{C}^\star} r_{u,C}\cdot y_{C,u} \geq req_u,\ \forall\ u\in\mathcal{U} \\ &\sum_{u\in\mathcal{U}_b} y_{C,u} \leq x_C,\ \forall\ b\in\mathcal{B} \end{aligned} \tag{1}$$

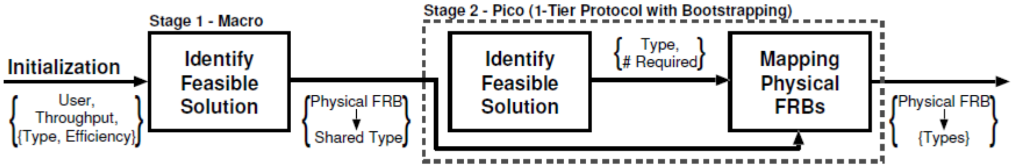
The first constraint guarantees a minimum throughput requirement req_u for each user u. The second constraint ensures that the total number of FRBs that are shared among the BSs in C and are allocated to the users served by each BS b is at most x_C.

Unfortunately, solving the LP problem in Equation (1) requires a centralized entity that has access to all information available at the BSs, i.e., rates $r_{u,C}$. However, even if a centralized agent could collect the rates from all BSs, solving the LP problem and communicating the solutions back to the BSs in a timely fashion would be difficult; the cardinality of $C^\star$ grows exponentially with the number of BSs $|B|$ in the network. For this reason, we focus on designing a *distributed* heuristic algorithm to approximate the centralized solution.

6 *Distributed Allocation*


Stage 1
Stage 2
Initialization
Identify Feasible Solution
Mapping Physical FRBs
User, Throughput, {Type, Efficiency}
Type, # Required
Physical FRB → {Types}

(a) 1-tier network allocation algorithm


Stage 1 - Macro
Stage 2 - Pico (1-Tier Protocol with Bootstrapping)
Initialization
Identify Feasible Solution
User, Throughput, {Type, Efficiency}
Physical FRB → Shared Type
Identify Feasible Solution
Type, # Required
Mapping Physical FRBs
Physical FRB → {Types}

(b) 2-tier network allocation algorithm

Figure 3: Schematic for distributed solutions; the 1-tier algorithm is used as a subroutine in the 2-tier allocation.

We first describe our technique on a PBSs only network, and later augment it to account for the MBS as well. As opposed to the frequency partitioning scheme, in our scheme, multiple BSs may transmit over the same FRB, even if they are neighbors of each other. To capture and facilitate sharing of FRBs, it is useful to classify FRBs into different *types*: In our model, a FRB is "owned" by a single BS that chooses to "share" the FRB with other BSs. We denote a FRB type by (o:v), where o is the owner BS and v is a subset of o's neighbors in the conflict graph. By denoting a FRB of type (o:v), the BS o chooses to share the FRB with BSs in the set v. The BSs in v may interfere with users served by o using the type (o:v). If v is empty, o claims the FRB for its own exclusive use. For example, the FRB type (1:2) denotes FRBs BS1 is willing to share with BS2.[1] Finally, note that (1:2) and (2:1) denote two different FRB types with two different owners.

Figure 3 shows a block-level decomposition of our algorithms; Figure 3a outlines the algorithm for 1-tier networks consisting of only PBSs, and Figure 3b illustrates our proposed scheme for heterogeneous 2-tier networks comprising both a MBS and PBSs.

6.1 PBS-only network (1-tier network)

Recall that we assume users associate with the BS that provides the highest SNR. With multiple overlapping transmission ranges and user positions, different users experience different levels of interference from the non-serving BSs. On one hand, in order to minimize the number of required FRBs, each BS selects FRB types for its users in a way that tries to maximize sharing with neighboring BSs. On the other hand, some users may be located close to neighboring BSs, sharing with neighboring BSs may not be beneficial for such users. Hence, it is important to consider the expected throughput of the users when served using shared FRBs. We capture this trade-off between sharing and expected throughput of a user using the *efficiency* of a FRB type for each user.

Users rank FRB types by their *efficiency*, defined as $r_{u,P(t)}/c(t)$ for a FRB type t=(o:v) and user u. $P(t)$ is the set of participating BSs in FRB type t, i.e., the BSs in $\{o\}\cup v$. $r_{u,P(t)}$ is the expected throughput of user u when it is served by a FRB shared among the set of BSs $P(t)$.

We define the cost of a FRB type as a function which has an inverse relationship to the amount of sharing. Let N_o be the set of all neighbors of BS-o. The cost of an FRB type t=(o:v) is given by $c(t)=1+|N_o\setminus P(t)|$, i.e., the number of neighbors of BS-o that are not allowed to share the FRB type plus one. For example, in Figure 2, a user in cell 2 that is relatively far from cell 3 might have average throughput of 800 kbps on type (2) FRB and a average throughput of 700 kbps on type (2:3) FRB. The efficiency of a type (2) FRB is 800/5, while the efficiency of type (2:3) FRB is 700/4. Thus, type (2:3) FRB is preferred over type (2) FRB for the user.

The input to the algorithm is the set of users along with their minimum required throughput and ranked list of FRB types. BSs undertake an iterative distributed procedure, described in Section 6.1, to find a feasible solution that meets the minimum throughput requirement for each associated user. The output of this step specifies how many FRBs of each type are required to accommodate all users. We take these requirements and use a distributed first-fit graph coloring heuristic to map compatible FRB type(s) to physical FRBs, as described in Section 6.2 .

6.2 2-tier network with MBS

Our complete solution, outlined in Figure 3b, considers an MBS as well and uses the 1-tier algorithm described above as a subroutine. In the rest of this report, we refer to this procedure as the 2-tier algorithm as it considers a heterogeneous network containing one MBS and multiple PBSs.

The input to the 2-tier algorithm is the same as the 1-tier network case. The MBS first creates a feasible FRB allocation for its users only. In doing so, the MBS may choose to share FRBs with some of the PBSs. We describe the procedure used by the MBS in Section 7. The PBSs then take the resulting FRB allocation from the MBS and run the 1-tier algorithm, initializing the mapping stage with the FRBs shared with the MBS.

---

[1] For brevity, we write (1:2) instead of (1:{2}).

7 *Distributed Algorithm for 1-tier Networks*

During the first stage of the scheme, each BS coordinates with neighboring BSs to decide the set of FRB types, to identify the set of FRBs that can be shared among different sets of BSs in order to reduce the number of physical FRBs needed to satisfy user throughput requirements. The second and the final stages map the FRB types determined in the first stage to physical FRBs while attempting to minimize the total number of FRBs.

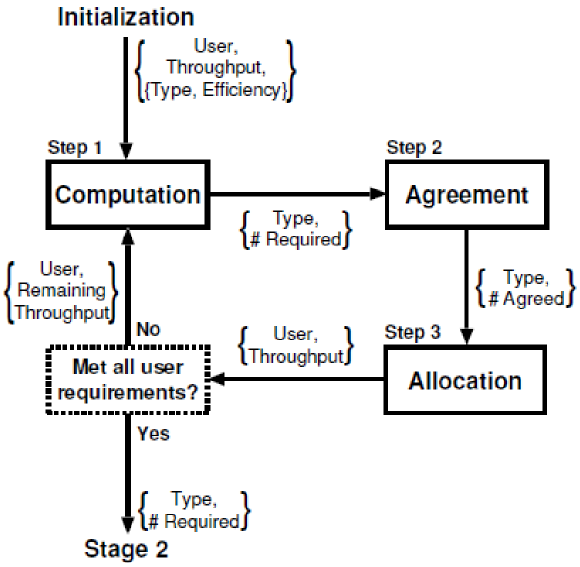
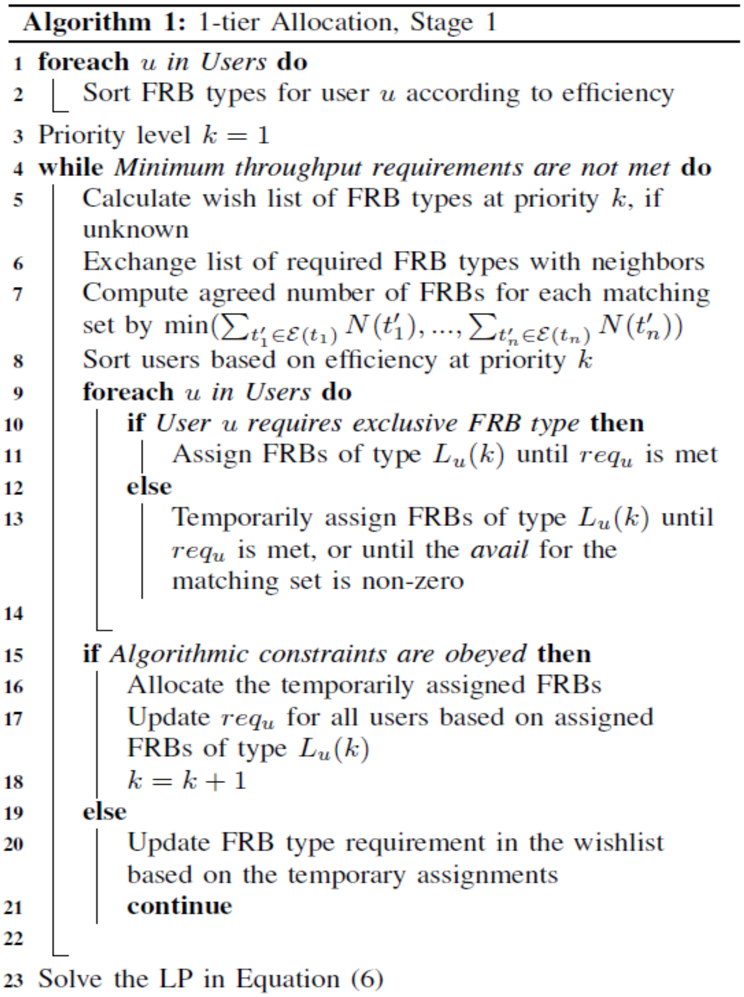

Initialization
User,
Throughput,
{Type, Efficiency}
Step 1
Computation
Type,
# Required
Step 2
Agreement
Type,
# Agreed
User,
Remaining
Throughput
No
User,
Throughput
Step 3
Met all user
requirements?
Allocation
Yes
Type,
# Required
Stage 2

Figure 4: Breakdown for stage 1 of the pico-only allocation algorithm

7.1 First stage

In the first stage, each BS attempts to find a *feasible* set of FRBs through an *iterative* procedure, shown in Figure 4, consisting of three steps in each round until it satisfies all users' requirements. During the first step, each BS computes a set of FRBs of different types in order to satisfy the user requirements, which we call its *wish list*. BSs then exchange wish lists with their neighbors and identify the set of FRBs which the participating BSs agree on, called the *agreed list*. Finally, each BS takes the FRBs in the agreed list and allocates them to its associated users. Each BS repeats these steps until its users' minimum requirements are met, after which it passes the number of each FRB type allocated in the first stage to the second stage.

We present the pseudocode for the first stage in Algorithm 1.



Algorithm 1: 1-tier Allocation, Stage 1

```
1  foreach $u$ in Users do
2      Sort FRB types for user $u$ according to efficiency
3  Priority level $k = 1$
4  while Minimum throughput requirements are not met do
5      Calculate wish list of FRB types at priority $k$, if unknown
6      Exchange list of required FRB types with neighbors
7      Compute agreed number of FRBs for each matching set by $\min(\sum_{t'_1 \in \mathcal{E}(t_1)} N(t'_1), \ldots, \sum_{t'_n \in \mathcal{E}(t_n)} N(t'_n))$
8      Sort users based on efficiency at priority $k$
9      foreach $u$ in Users do
10         if User $u$ requires exclusive FRB type then
11             Assign FRBs of type $L_u(k)$ until $req_u$ is met
12         else
13             Temporarily assign FRBs of type $L_u(k)$ until $req_u$ is met, or until the avail for the matching set is non-zero
14
15     if Algorithmic constraints are obeyed then
16         Allocate the temporarily assigned FRBs
17         Update $req_u$ for all users based on assigned FRBs of type $L_u(k)$
18         $k = k + 1$
19     else
20         Update FRB type requirement in the wishlist based on the temporary assignments
21         continue
22
23 Solve the LP in Equation (6)
```

The main steps of the algorithm with the corresponding line numbers in the pseudocode are listed below. A detailed explanation of each step can be found in [20].

(a) Initialization

(b) Step 1 - Computation (Line 5)

(c) Step 2 - Agreement (Line 6-7)

(d) Step 3- Allocation (Lines 8-21)

7.2 Second stage

The first stage computes the required FRBs of each type, but does not allocate them to *physical* FRBs. For example, consider a conflict graph that is not connected such that we can partition it into two disjoint subgraphs. It is clear that we could allocate a single physical FRB to both sets with no resulting interference. The second stage serves to establish this physical FRB allocation.

We formulate the problem of mapping requested FRBs in the first stage to physical FRBs as a vertex coloring problem. The vertices of the graph are the requested FRBs of all BSs, where edges exist between two vertices when they are unable to be mapped to the same physical FRB due to interference. The number of colors required to color the graph is equal to the number of physical FRBs required to satisfy the output from the first stage.

Since the coloring problem is NP-Hard, we employ a distributed greedy first-fit approximation algorithm [21] for the coloring problem: We map the requested FRB types of each BS to the first physical FRB that can accommodate the FRB type. FRB of type *t* can be mapped to a physical FRB, if all the following conditions are met:

(a) The owner of the FRB type *t* cannot own any other FRB type already mapped to the physical FRB.

(b) The neighbors of BS *O*(*t*) which are not included in the set *P*(*t*), i.e., $N_{O(t)} \setminus P(t)$, constitute a complement set of BSs for type *t*. Any BS in the complement set of type *t* should not be a participating BS of any FRB type already mapped to this physical FRB.

(c) Any BS in the union of the complement sets of FRB already mapped to the physical FRB should not be in *P*(*t*).

Using the example in Figure 2, consider the addition of type (3:∅) to a physical FRB that is already assigned to type (2:4,5). In this case, the above conditions (b) and (c) for compatibility are not met. Therefore, we cannot map type (3:∅) to this physical FRB. On the other hand, type (5:2) satisfies all of the compatibility requirements.

If we cannot map a FRB type to physical FRBs that are already assigned to other FRB types, we assign it to a new physical FRB. The algorithm repeats until we map all FRB type requirements to physical FRBs.

Our algorithm is designed to minimize the total number of physical FRBs required to accommodate the throughput requirements of all users in the system. However, it can also handle a scenario where we are given a set of available physical FRBs to allocate as follows: We first compute an initial allocation to meet users' requirements, making use of our algorithm. Then, excess FRBs are assigned to the users in proportion to the initial allocation. Thus, each user in the system would get a throughput that is proportional to its minimum requirement.

7.3 Example allocation

We provide an example to demonstrate the benefit of our 1-tier allocation approach over other schemes such as reuse-1 and exclusive frequency allocation. Consider a portion of the topology shown in Figure 2 consisting of PBS$_1$, PBS$_2$, and PBS$_5$. We assume user Alice is associated with PBS$_1$, Bob associated with PBS$_2$, and Carol associated with PBS$_5$. The rate for each FRB type for all users are listed below (in kbps), sorted in decreasing order of efficiency.

Alice	Bob	Carol
(1:2)→270	(2:1)→360	(5:1,2)→270
(1:∅)→360	(2:∅)→360	(5:2)→360
(1:2,5)→90	(2:1,5)→120	(5:1)→270
(1:5)→120	(2:5)→180	(5:∅)→360

Assume each user requires an average throughput of 1000 kbps.

1. *Priority k=1:* BS-1 requires 4 FRBs of type (1:2) for Alice, BS-2 requires 3 FRBs of type (2:1) for Bob, and BS-5 requires 4 FRBs of type (5:1,2) for Carol. The agreed list for this round consists of 3 FRBs of types (1:2) and (2:1), according to the constraint that *N*((1:2))=*N*((2:1)). We update Alice's residual throughput requirement to 1000−3*270=190 kbps, and Bob's residual throughput requirement to 0 kpbs. BS-2 stops participating in the algorithm as it has satisfied all user requirements.

2. *Priority k=2:* BS-1 requires 1 FRB type (1:∅) for Alice, and BS-5 requires 3 FRBs of type (5:2) for Carol. Since BS-1 is only interested in allocating exclusive subcarriers, it satisfies Alice's residual throughput requirement and sets it to 0 kpbs. The agreed list for this round is empty. BS-1 stops participating in the algorithm as it has satisfied all user requirements.

3. *Priority k=3:* BS-5 requires 4 FRBs of type (5:1) for Carol. The agreed list for this round is empty again.
4. *Priority k=4:* BS-5 requires 3 FRBs of type (5:∅) for Carol. Since BS-5 is only interested in allocating exclusive subcarriers, it satisfies Carol's throughput requirement and sets it to 0 kpbs. The agreed list for this round is empty. BS-5 stops participating in the algorithm as it has satisfied all user requirements.

The final list of requirements from the first stage is given in the table below. Since (1:2) and (2:1) are compatible, this allocation requires a total of 7 physical FRBs.

FRB	# Required
(1:2), (2:1)	3
(1:∅)	1
(5:∅)	3

In contrast to our allocation scheme, the reuse-1 algorithm requires $\lceil 1000/90 \rceil = 12$ FRBs and the exclusive frequency allocation algorithm requires $3 * \lceil 1000/360 \rceil = 9$ FRBs.

8 Distributed Algorithm for 2-tier Networks

While we can apply the proposed 1-tier algorithm for use in 2-tier networks, the performance degrades (increased complexity) when applied to conflict graphs in which nodes have high degrees. Since we assume all users associated with a PBS see interference from the MBS, the MBS node in the conflict graph has degree $|\mathcal{B}|-1$. Therefore, we propose a new algorithm for 2-tier networks which handles users associated with the MBS, removing the need for PBSs to consider the MBS.

In addition, we group the PBSs into *clusters* to simplify allocation and reduce the computational complexity of our algorithm. Clusters capture the topological structure in practical deployments, and consist of a group of PBSs within an area such as a stadium or shopping mall. Consider a graph where the vertices correspond to the PBSs. Edges exist between two PBSs if their distance is less than a given threshold d, where d is chosen such that inter-cluster interference is negligible. Each connected component in this graph corresponds to a cluster of PBSs.

We propose a two stage algorithm for allocation in 2-tier networks. The MBS first allocates physical FRBs to satisfy its associated users, and sends out allocation information which pertains to the clusters. The PBSs in each cluster run the 1-tier algorithm to satisfy user requirements, bootstrapping with the physical FRBs from the MBS. A detailed explanation of the two stages is given in [20].

A key idea that we exploit in our algorithm is the following: Since we assume that different clusters of PBSs cause minimal interference to PBSs in other clusters, any FRBs used by some cluster of PBSs (which are not shared with the MBS) can be shared with all other clusters of PBSs with minimal interference. Suppose that each cluster ℓ of PBSs ($\ell=1,2,\cdots,H$) computes the number of additional FRBs of each type it needs to satisfy the minimum throughput requirements of the users served by the cluster, which we denote by ξ_ℓ. Based on the above observation, the total number of FRBs we need is approximately equal to the sum of the FRBs needed by the MBS (including those shared with PBSs) and the maximum among the additional required FRBs of the clusters, i.e., $\max_{\ell=1,2,\ldots,H} \xi_\ell$

8.1 Dynamic allocation

We also consider a dynamic system where the user population varies with time as opposed to the static case considered in previous sections. Every instance of departing user associated with a BS creates a slack of FRBs of the type allocated previously to the departing user at the BS. An FRB slack at a BS is defined as the set of FRBs available to the BS but not currently allocated to any user associated with the BS.[2] In the 2-tier algorithm, the MBS shared physical FRBs may be sufficient to satisfy the throughput requirements of the users associated with the PBSs. Further, the surplus MBS shared FRBs create an 'implicit slack' at the PBSs. The PBSs can share surplus physical FRBs based on the associated MBS shared FRB types. An arriving user can associate with a BS which can satisfy the requirement of the user with the available slack of FRBs. Thus, given sufficient slacks, the FRB allocation to arriving user does not require any additional FRBs.

We propose a greedy joint association and FRB allocation scheme for the dynamic system using the slack of FRBs available at BSs. The pseudocode and explanation of the scheme is provided in [20].

9 *Results and Discussion*

We evaluate our 1- and 2-tier allocation algorithms and compare them to the following allocation algorithms:

- Centralized LP allocation
- Partitioned pico
- Centralized macro-pico allocation
- Frequency reuse algorithm [12] for conventional homogeneous networks
- User coloring algorithm [18]

A detailed description of the simulation parameters and scenarios along with a description of the above algorithms can be found in [20].

9.1 1-tier algorithm

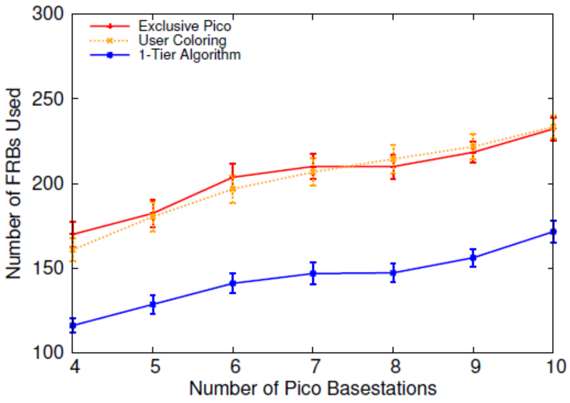


Figure 5: Number of required FRBs in a 1-tier network with varying number of PBSs.

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[2] In practice, these extra FRBs will be reallocated to other users to increase their throughput.

Unlike the PBS partitioning scheme that allocates exclusive FRBs to neighboring PBSs, our 1-tier algorithm allows sharing of FRBs among interfering BSs. As a result, the 1-tier algorithm requires at least 26% fewer FRBs, which demonstrates the advantage of sharing FRBs even amongst interfering PBSs. The user coloring scheme uses on average 42% more FRBs than the 1-tier algorithm when there are 7 PBSs. This is because the user coloring scheme uses a fixed SINR threshold to decide the type of sharing for a physical FRB, as opposed to explicitly accounting for the efficiency of FRBs of different types.

9.2 2-tier algorithm

In the rest of this section, we focus on the 2-tier algorithm. We study its performance as the number of PBSs, the number of MBS, level of interference among the PBSs, and number of users are varied with time, and compare the number of required FRBs to that of the centralized LP and other existing schemes.

(a) Effects of increasing network size

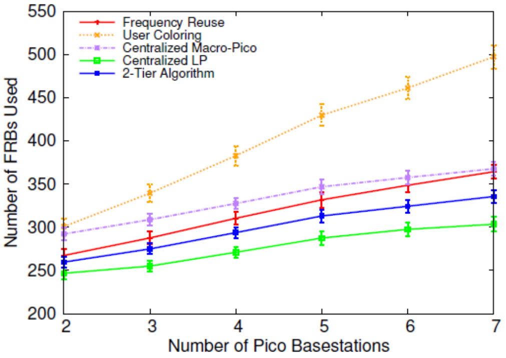

Figure 6: Number of required FRBs with varying number of PBSs (2-tier network).

With an increasing number of PBSs, the number of FRBs needed is expected to increase. However, the ability to share amongst PBSs also increases with the number of PBSs. As shown in Fig. 6, the 2-tier algorithm performs well (within 11% of the centralized LP solution for all scenarios). In contrast, the frequency reuse [12] scheme is 8.3-20% worse. The centralized macro-pico allocation scheme also performs worse than the 2-tier algorithm, illustrating the benefits of sharing FRBs between MBS and PBSs.

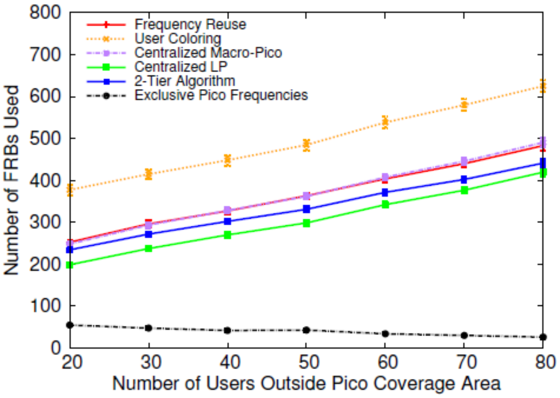

Figure 7: Number of required FRBs with varying number of users outside PBS coverage area.

(b) Effects of the load on MBS

Figure 7 shows that as the fraction of users served by the MBS increases, the MBS is able to share more FRBs with PBSs. The 2-tier algorithm first allocates the FRBs shared with the MBS to PBSs in the second stage before checking the needs for FRBs exclusive to PBSs. Since the number of users in the coverage area of a PBS is fixed, as shown in Figure 7 (labeled as "Exclusive Pico Frequencies"), the number of FRBs exclusive to PBSs decreases from 23% of the total number of FRBs to 6% as the number of MBS users increases from 41.3% to 56%.

In addition, as the number of MBS users increases, the performance of 2-tier algorithm approaches that of the centralized LP solution. The 2-tier algorithm is only 5.2% worse than the LP when the fraction of MBS users is 56%, while it is 17.9% higher with 41.3% MBS. This is because as the MBS serve more users, it is able to share more FRBs with the PBSs. As a result we require fewer FRBs exclusive to the PBSs. In contrast, the centralized macro-pico allocation scheme that does not allow MBS and PBSs to share FRBs is not able to utilize these sharing opportunities. Consequently, the gap between the 2-tier algorithm and the centralized macro-pico allocation scheme widens with increasing MBS users. Finally, note that the user coloring [18] and frequency reuse [12] schemes perform consistently worse, as they are also unable to take advantage of the sharing opportunities.

(c) Effects of PBS clustering

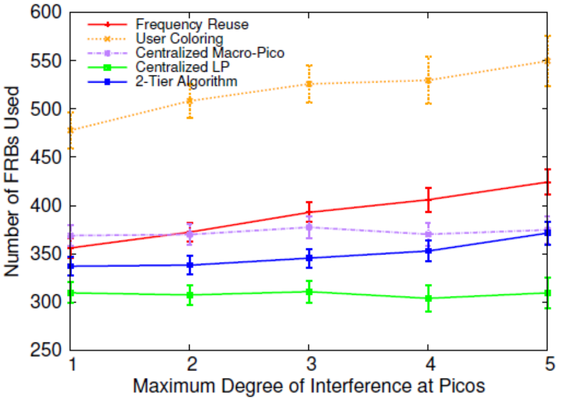

Figure 8: Number of required FRBs with varying maximum degree of PBSs in the conflict graph.

Here, we investigate the effects of the level of clustering among the PBSs on the performance of the schemes. We place 7 PBSs in varying configurations such that the level of interference among the PBSs changes. Figure 8 plots the number of required FRBs as a function of the maximum degree among the PBSs in the conflict graph. The average numbers of clusters for maximum degree of 1, 2, 3, 4 and 5 are 7, 5.7, 4.6, 3.75 and 2.9, respectively. As expected, the number of FRBs required by the 2-tier algorithm is positively correlated with the maximum degree (and hence inversely with the number of clusters). Also, the centralized macro-pico allocation scheme does not perform well when the maximum degree is small since the MBS is not permitted to share FRSs with PBSs.

As the PBSs cluster together, the opportunity to share FRBs with many PBSs diminishes and, consequently, the number of required FRBs goes up. Moreover, as the clustering increases and it becomes more difficult for the PBSs to share FRBs with the MBS, the performance of the 2-tier algorithm approaches that of the centralized macro-pico allocation scheme. In fact, in the worst case where no sharing is possible, the 2-tier algorithm performs worse than the centralized macro-pico allocation scheme. This is due to the fact that the latter employs an optimal allocation among the PBSs by solving the centralized LP, whereas the 2-tier algorithm adopts a distributed heuristic algorithm.

(d) Scenarios with user arrivals and departures

We study how varying the period between optimizations affects the overall performance when considering user arrivals and departures, as described in Section 7.1. We evaluate the greedy joint allocation scheme with time-varying user population in a network consisting of two PBSs and an MBS. Our simulations in [20] demonstrate a clear tradeoff between the performance of the dynamic allocation and the frequency at which we execute the 2-tier algorithm. Moreover, the 2-tier algorithm performs comparably to the the centralized LP.

10 Conclusion

We have introduced and evaluated a new algorithm for frequency allocation in 2-tier heterogeneous networks. Our algorithm is completely distributed, requires little coordination between various BSs, and is able to effectively share frequency resources between an MBS and PBSs. Our algorithm is more efficient than previously known distributed schemes, and performs nearly on-par with centralized LP-based optimal solutions if the PBS deployments allow for spatial frequency reuse.

There remain many open issues we have not investigated here. For instance, we have not explored the possibility of joint association and resource allocation and design of distributed algorithms. We plan to examine these open issues in the future and study how much benefit we can achieve through joint design of association and allocation schemes.

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11 List of Acronyms

BS	Base Station
DIM	Distance Interference Model
FRB	Frequency Resource Block
Kbps	kilobits per second
LP	Linear Programming
MBS	Micro Base Station
PBS	Pico Base Station
SINR	Signal to Interference plus Noise Ratio
SNR	Signal-to-noise ratio